COHERENT BLOCH OSCILLATIONS IN SUPERLATTICES
EXCITED BY 1.55 μm fs-LASERPULSES

Final Report
by

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(February 1999)

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London, England

CONTRACT NUMBER N69171-M-97-M-5821
R&D 8358-EE-01

Prof. Heinrich Kurz

Approved for Public Release; distribution unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
February 1999

3. REPORT TYPE AND DATES COVERED
Final (1 Jan 98 - 31 Dec 98)

4. TITLE AND SUBTITLE
Coherent Bloch oscillations in superlattices excited by 1.55 μm fs laser pulses

5. FUNDING NUMBERS
C N69171-97-M-5821
R&D 8358-EE01

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USARDSG-UK, Edison House, 223 Old Marylebone Road,
London NW1 5TH, UK

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The aim of this project is the investigation of coherent Bloch oscillations in superlattices excited by fs optical pulses in the 1.55 μm wavelength range. One potential application of Bloch oscillations is the electromagnetic radiation emitted from this system tunable from several hundred GHz to some THz by changing the voltage applied to the superlattice.
The investigations were performed by fs optical pump-probe spectroscopy in strain-balanced InGaAs(P) based heterostructures grown by MOVPE. Bloch oscillations have been observed for the first time in ternary InGaAs/InGaAs superlattices at low latice temperatures. The dephasing time of the oscillations was found to be only a factor of 3 smaller compared to the mature GaAs/AlGaAs material system grown by MBE. It could be observed that the oscillation frequency changes in time. The analysis of this effect has lead to important insights into the the transport and scattering dynamics in this material on the sub-picosecond time scale. It was found that scattering with thermally populated LO phonons is a limiting factor for the room temperature operation Bloch oscillations.
The obtained results give important hints for the further optimization of the superlattices concerning material composition and device design.

14. SUBJECT ITEMS
Bloch oscillations, superlattices, 1.55 μm, THz radiation, quantum coherence

15. NUMBER OF PAGES
11

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Contents

1 Introduction

The aim of this seed project is the investigation of continuously tunable emitters of electromagnetic radiation in the range of 100 GHz up to several THz based on the excitation of coherent Bloch oscillations in superlattices at optical wavelengths of 1.55 μm. The most suitable devices for this purpose are superlattices composed of InGaAs(P) layers on an InP substrate. They offer the tunability of excitonic optical transitions to the relevant wavelengths. The optimization of these heterostructures with respect to the efficiency for the excitation of Bloch oscillations and the associated emitted THz radiation is an important objective of the project. The InGaAs(P)material system has unique properties for achieving this objective. Once the devices are optimized for room temperature operation, the use of compact femtosecond laser sources based on Erbium-doped fibers at 1.55 μm as optical excitation sources should lead to the feasibility of producing compact tunable THz emitters.

In a biased superlattice, Bloch oscillations are optically generated by the coherent superposition of Wannier-Stark states by an ultrashort laser pulse. The oscillatory motion of the excited electronic wave packet represents the semi-classical picture of Bloch oscillations proposed by Esaki and Tsu in 1970 [1]. The oscillations' frequency is given by the energy splitting between the excited states, i.e. $\nu = eFd/h$, where F is the applied electric field and d the superlattice period. Thereby, the time-dependent dipole consisting of the oscillating electronic wavepacket and the localized holes results in the emission of electromagnetic radiation with frequencies in the THz range. The tunability of this THz emitter is accomplished by changing the electric field applied to the superlattice.

Bloch oscillations have been observed for the first time in an GaAs/AlGaAs superlattice by four-wave mixing experiments in 1992 [2, 3]. The emission of the coherent THz radiation associated with the oscillating dipole was first demonstrated in an GaAs/AlGaAs superlattice in 1993 in our institute [4]. Two years later, the generation of Bloch oscillations was achieved at room temperature in the same material system [5]. The MBE (molecular beam epitaxy) grown GaAs/AlGaAs samples offer exceptionally high quality with respect to their electrical and optical properties while the optical excitation wavelengths are in the range of 800 nm covered by Ti:sapphire lasers. In 1996, Bloch oscillations were detected in the first material system different from the GaAs/AlGaAs system, i.e. in a strain-balanced InGaAsP/InGaAsP superlattice grown by low-pressure molecular vapor phase epitaxy (LP-MOVPE) [6]. Compared to the MBE-grown GaAs/AlGaAs superlattices, shorter dephasing times of the Bloch oscillations have been observed in the InGaAsP LP-MOVPE grown system due to the inferior sample quality. Up to now, the room temperature observation of Bloch oscillations could not be performed in these devices. This disadvantage is expected to be overcome by an optimization of the growth processes and device design for InGaAs(P) based superlattices.

2 Results

Important results on the coherent carrier dynamics, i.e. Bloch oscillations, *and* the incoherent carrier dynamics in the investigated devices have been obtained. Bloch oscillations have been detected for the first time in a ternary InGaAs/InGaAs superlattice. The feasibility of observing Bloch oscillations in this material system at room temperature, the ultrafast thermalization of optically excited excitons has been investigated in InGaAsP/InGaAsP multiple quantum wells (MQW). It has become obvious that the investigated shallow InGaAs/InGaAs superlattices grown by LP-MOVPE do presently not exhibit the dephasing times necessary for achieving room temperature operation. The Bloch frequencies in these samples were found to be time dependent, i.e. chirped. This chirp - although undesired for device operation - provides an important access to a quantitative analysis of the transport dynamics in this important material system on a sub-picosecond time scale. These results are equally important for the optimization of ultrafast Wannier-Stark modulators relevant for optical communication at 1.55 μm.

A solution against the undesired chirp should be the growth of InGaAs/InAlAs superlattices by MBE, since MBE-grown GaAs/AlGaAs superlattices with larger dephasing times do not show this time-dependent frequency shift. The design and growth of such devices has been discussed with Dr. R.P. Lea-

vitt (Adelphi Labs.). The proposed optimization of the devices, which was not possible within the 1 year project duration, should be pursued in the future.

The thermalization of resonantly excited excitons was found to be a limiting factor for room temperature operation of Bloch oscillations. This was demonstrated in an InGaAsP/InGaAsP multiple quantum well where scattering with thermally populated longitudinal optical phonons leads to an ionization of the excitons within 200 fs.

The characterization of the static properties of the investigated MOVPE-grown superlattice sample is followed by a description of the experimental details of our investigations. Femtosecond time-resolved experiments performed within the project are introduced. The detailed analysis of the experiments includes a theoretical study of the carrier transport in the investigated superlattice.

The results obtained in this first project year show a clear route to be followed for the further optimization of superlattices. Especially with regard to the access to MBE grown samples provided by the growth facilities in Adelphi Laboratories, we expect to achieve longer dephasing times and higher temperature operation.

2.1 Sample design and characterization

The investigated $In_{x_w}Ga_{1-x_w}As/In_{x_b}Ga_{1-x_b}As$ superlattice sample was grown by LP-MOVPE in the Institute of Semiconductor Electronics I (Prof. K. Heime) at the RWTH Aachen. The strain-balanced superlattice consists of ten periods of 7 nm thick, compressed $In_{0.59}Ga_{0.41}As$ wells and 8 nm thick, tensile strained $In_{0.40}Ga_{0.60}As$ barriers. The active layers are embedded in the intrinsic region of a p-i-n diode of lattice-matched $In_{0.84}Ga_{0.16}As_{0.34}P_{0.66}$ grown on an n:InP substrate. The conduction band offset in this shallow superlattice is approximately 90 meV offering favorable properties of the vertical carrier transport, i.e. along the superlattice growth direction. The calculated electronic miniband width is 22 meV. This miniband width should support a tunability of Bloch oscillations up to approximately 5 THz.

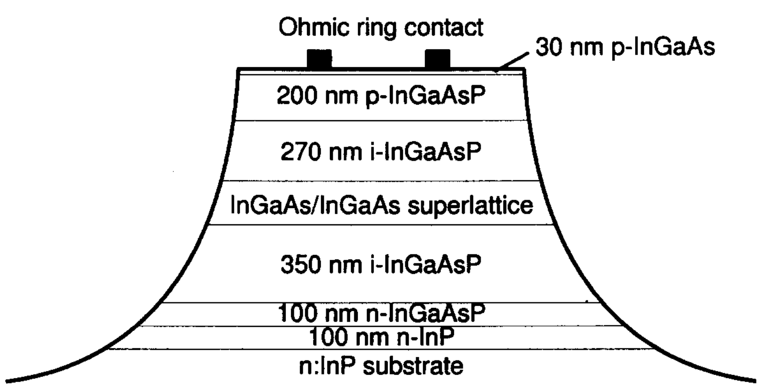

Figure 1: Design of the superlattice mesa structures.

Mesa structures with an inner diameter of about 100 μm were fabricated on the substrate (see Fig. 1). An Ohmic ring contact consisting of 25 nm Pd followed by 200 nm Au is vaporized on the p-doped top. The highly doped substrate is polished mechanically to enable transmission measurements. Afterwards the sample is glued on a sapphire substrate. The samples are contacted by bonding wires on the top and conductivity paste on the substrate, respectively. The mesa structures avoid electric field inhomogenities and reduce the possibility of field breakdowns at alloy impurities.

The sample was characterized by static photocurrent spectroscopy. Fig. 2 shows the detected photocurrent spectra at a lattice temperature of 77 K and applied biases from +0.5 V (flatband) to -0.95 V. The Wannier-Stark (WS) ladder, i.e. the linearly increasing energy splitting of the WS transitions with increasing electric fields, of the first excitonic transition is resolved at energies near 0.8 eV. This energy

range equals optical wavelengths around 1.55 μm. At high fields, the electronic wavefunctions are localized in single wells resulting in a red shift of the WS(0) transition due to the quantum confined Stark effect (QCSE).

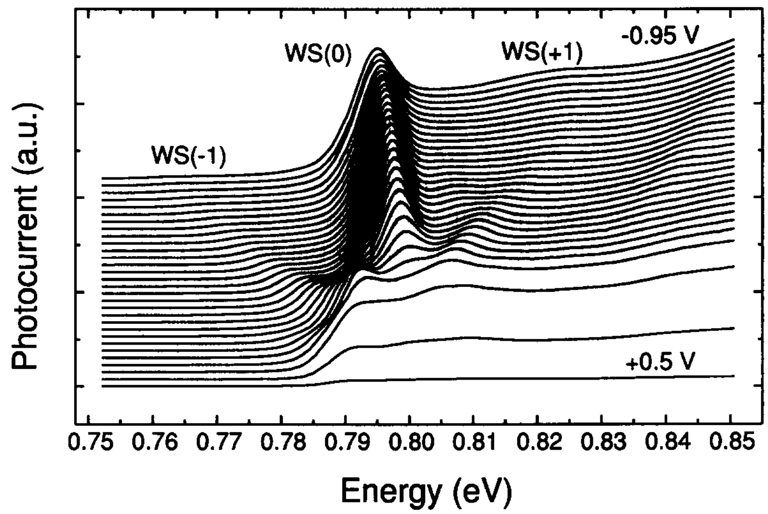

Figure 2: CW photocurrent spectra of the investigated superlattice at a lattice temperature of 77 K.

2.2 Experimental setup

An important key for our investigations is the availability of femtosecond pulses in the 1.55 μm range. The laser source for these experiments is a singly-resonant optical parametric oscillator (OPO) that is tunable from 1.1 μm to 2.2 μm with two different mirror sets. It is pumped by a femtosecond passively mode-locked Ti:sapphire laser (TSUNAMI, Spectra Physics Inc.) at 800 nm with a repetition rate of 82 MHz. The conversion of the optical frequency in the OPO (OPAL, Spectra Physics Inc.) is achieved by nonlinear processes in a Lithium-Triborate (LBO) crystal under simultaneous energy and momentum conservation (parametric amplification). The output wavelengths is controlled by the crystal temperature. The pulse lengths achieved by this system are below 200 fs at a wavelength of 1.55 μm.

Time-resolved investigations were performed by pump-probe spectroscopy in transmission geometry. Here, transmission changes of the sample induced by the optical pump pulse are detected as a function of time delay by the probe pulse. The time delay between the two pulses is achieved by a retro-reflector mounted onto a shaker driven at a frequency of 70 Hz. This techniques give a signal-to-noise ratio superior to conventional techniques based on a lock-in amplifier and a slow moving translator delay stage. The fast-scanning system developed in our institute has been made commercially available, recently [8].

The transmission changes are obtained by the subtraction of the transmitted intensity from the intensity of a reference beam that is split out of the probe beam in front of the sample. In combination with the fast delay line and a fast A/D converter, the fast scanning technique allows the detection of transmission changes up to the order of some $10^{-7}\Delta T/T_0$ within some minutes [8].

2.3 Scientific results

Within the project, Bloch oscillations have been detected for the first time in a ternary $In_{x_w}Ga_{1-x_w}As/In_{x_b}Ga_{1-x_b}As$ superlattice excited by 1.55 μm laser pulses. This observation was performed at low lattice temperatures. It is found that the coherent electronic motion is influenced by an incoherent transport of scattered Bloch electrons. A numerical simulation based on a drift-diffusion

model was developed to describe the Drude-like transport and to calculate associated changes of the electric field in the superlattice. Theoretical and experimental results are in a good agreement and, thus, give detailed insight into the sub-picosecond carrier dynamics.

The feasibility of the generation of Bloch oscillations at room temperature has been addressed. Since the resonant optical excitation is always based on the creation of excitons, the temperature dependence of the thermalization of optically excited excitons has been investigated. These experiments have been performed in an $In_{x_w}Ga_{1-x_w}As_{y_w}P_{1-y_w}/In_{x_b}Ga_{1-x_b}As_{y_b}P_{1-y_b}$ multiple quantum well. It is found that exciton ionization induced by scattering with thermally populated longitudinal optical (LO) phonons occurs within 200 fs at 300 K, thus imposing a lower limit to the frequency range in which Bloch oscillations can be expected to be observed at room temperature. This exciton ionization time corresponds to a lower frequency limit of approximately 4 THz.

2.3.1 Detection of Bloch oscillations in an InGaAs/InGaAs superlattice

Since the first detection of Bloch oscillations in four-wave mixing experiments in 1992 [2, 3], several techniques have been developed for their time-resolved observation [4, 6, 7]. They allowed to distinguish between the dephasing of different coherent polarizations, i.e. ***interband*** and ***intraband*** polarizations, that are created by the exciting laser pulses. Within this project, we detected Bloch oscillations in time-resolved transmission spectroscopy that is sensitive to the ***intraband*** coherence between the superposed WS states in the conduction band [6]. If Bloch oscillations are generated, the resonantly detected transmission changes contain oscillating contributions due to the time-dependent bleaching of the coherently superposed WS transitions that are periodically modulated with the Bloch frequency.

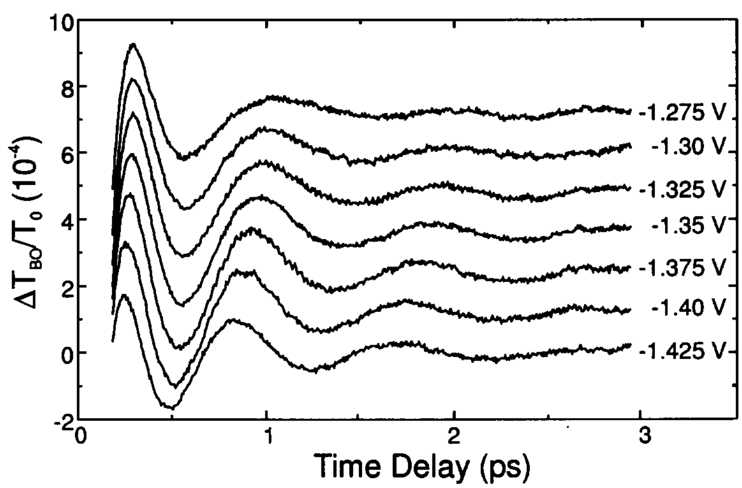

Figure 3: Bloch oscillations extracted from time-resolved transmission changes in the InGaAs/InGaAs superlattice at different reverse biases and 10 K lattice temperature. The excitation energy is 0.792 eV and the excitation density is 1.2×10^{15} cm^{-3}.

Fig. 3 shows the numerically extracted oscillatory components $\Delta T_{BO}/T_0$ of time-resolved transmission changes detected in the InGaAs/InGaAs superlattice at 10 K lattice temperature. The spectral profiles of the pump and probe pulse cover the WS(0) and the WS(-1) transitions. The excitation density is 1.2×10^{15} cm^{-3} to minimize the influence of carrier-carrier scattering on the dephasing of the Bloch oscillations. An increase of the initial frequency – given by the period of the first cycle – with increasing reverse bias is clearly visible manifesting the detection of Bloch oscillations. The lowest frequency is 1.3 THz, while the upper frequency is 1.7 THz. The upper limit is given by the spectral width of the exciting laser pulses and not by the miniband width. The slope of the initial frequency versus the applied bias is 3.5 THz/V which is close to the value of 4.0 THz/V calculated from the energy

gap between the WS(−1) and the WS(0) transitions in the photocurrent spectra. In addition, a linear chirp, i.e. a linear frequency shift with time, of the Bloch oscillations is clearly visible. Since the Bloch oscillations' frequency depends linearly on the electric field, the chirp is interpreted as resulting from a transient screening of the applied electric field. This screening is induced by a drift current of electrons after scattering processes, e.g. scattering on interfaces and impurities, or carrier-carrier-scattering. These processes lead to a dephasing of the electronic ***intraband*** coherence and thus to the observed net drift current.

The dephasing time of the Bloch oscillations is determined to 0.7 ps in our sample. This value is a factor 3 smaller than the best values obtained in an unstrained GaAs/AlGaAs superlattice at comparable excitation densities [7]. Assuming comparable carrier-carrier scattering rates, the large difference in the dephasing times is attributed to an increase of the electron scattering at interfaces and alloy impurities. This effect shows that efficient generation of Bloch oscillations strongly depends on the quality of the superlattices, i.e. the presence of strain and the growth method, respectively. Especially, in MBE-grown GaAs/AlGaAs superlattices a transient frequency shift was not yet observed at low lattice temperatures. This may originate from the difference in the conduction band offsets between wells and barriers in these material systems. Typical values for this offset are several 100 meV in the GaAs/AlGaAs structures but below 100 meV in shallow InGaAs/InGaAs superlattices. At comparable miniband widths, the miniband mobility is then expected to be enhanced in the shallow superlattices. The higher mobility leads to a transient field screening which becomes detectable within the dephasing time of the Bloch oscillations.

The faster dephasing time and the observed frequency shift in the investigated InGaAs/InGaAs superlattice in comparison with experiments in the GaAs/AlGaAs system show that the performance of Bloch oscillations excited by 1.55 μm optical pulses has still a potential for further optimization. Larger dephasing times are expected for unstrained MBE-grown samples with increased barrier heights, e.g. InGaAs/InAlAs superlattices grown lattice-matched on an InP substrate.

For a detailed analysis of the incoherent transport the chirped Bloch oscillations were investigated at various excitation conditions, e.g. initial electric fields and excitation densities. In a first step, the linear field screening velocity $(\partial F/\partial t)$ was determined at different initial field strengths F_0 at a constant excitation density. This velocity is proportional to the vertical velocity of the electrons after excitation and thus should give insight into the transport dynamics. Fig. 4 depicts that at a constant

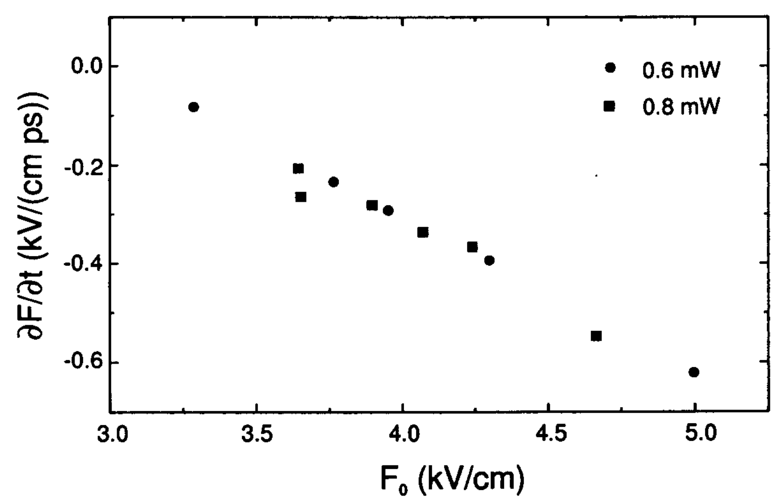

Figure 4: Transient electric field changes $(\partial F/\partial t)$ as a function of the initial field strength for two different excitation densities.

excitation density the amount of field changes increases linearly with initial field strengths. This means that the velocity of the carriers that contribute to the drift current increases at higher initial fields

pointing towards a drift-like transport of the carriers along the superlattice growth direction. A detailed, numerical analysis of this transport, containing a theoretical model and the determination of the electron mobility, will be given in Sect. 2.3.2.

An important parameter of the electric field screening is the excitation density. Thus, a density dependent analysis of the picosecond carrier dynamics in the superlattice was performed. The results are shown in Fig. 5. The inset of the figure depicts the initial electric field strengths versus the average pump power obviously showing that the initial field strength decreases with increasing excitation densities. This effect results from a quasi-static screening of the applied electric field by accumulated carriers. The electrons have been swept out of the superlattice layers and accumulate at the barrier of the InGaAsP buffer layer to the InP substrate on the time scale of the inverse laser repetition rate. In turn, this quasi-static screening strongly affects the carrier dynamics in the superlattice by its influence on the initial electric field strength. The enhanced quasi-static screening at increased excitation densities leads to a reduced velocity of the scattered Bloch electrons, while increased carrier densities result in an enhanced dynamic screening given by the solution of Poisson's equation. Fig. 5 shows that the amount of the dynamic screening increases with decreasing excitation densities clearly showing that the quasi-static field screening is the dominant effect that determines the transient field screening in this specific sample structure.

It was shown that incoherent carrier dynamics strongly influence the coherent dynamics of Bloch electrons. Thus, the obtained results give a fundamental insight into the interplay between coherent and incoherent carrier dynamics in semiconductors.

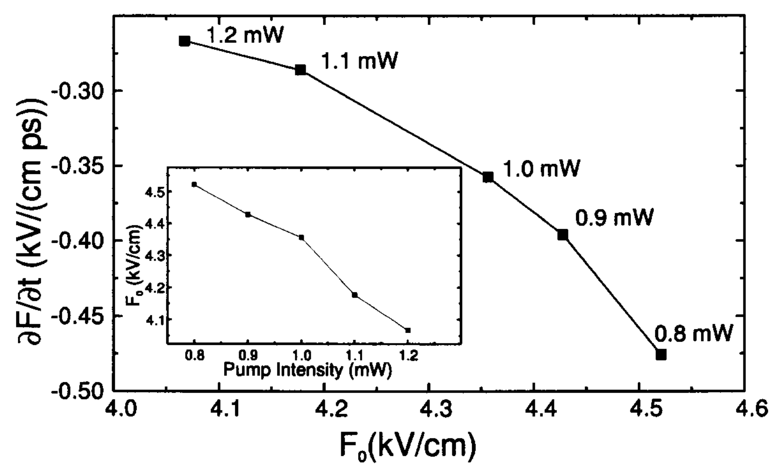

Figure 5: Initial field strengths (shown in the inset) and transient changes of the electric field detected at a constant reverse bias for different pump powers.

2.3.2 Numerical simulation of sub-picosecond carrier transport in the superlattice

The transient linear frequency changes of the Bloch oscillations were interpreted as resulting from a drift-like like transport of scattered Bloch electrons. For a determination of the relevant transport parameters, a one-dimensional numerical simulation of the vertical electron transport based on a drift-diffusion model was developed. This simulation enables the self-consistent calculation of changes in the electric field that are induced by the generation and the vertical transport of the generated carriers.

One important transport parameter is the mobility of the carriers. This can simply be derived from the electric field screening ($\partial F/\partial t$) and the initial field strengths F_0 obtained in the experiment. Under the neglection of hole transport due to their high effective masses, the electron mobility is then given by

$$\mu_e = \frac{\epsilon\epsilon_0}{en} \frac{\partial F/\partial t}{F_0} \tag{1}$$

yielding a value of 460 cm^2/Vs in the investigated superlattice.

For a comparison between experiment and theory, the one-dimensional drift-diffusion model was solved numerically. Thereby, the time and space dependent densities of electrons and holes are calculated. The associated electric fields are calculated by solving Poisson's equation. It has become obvious that two alternative generation rates of the carriers contributing to the incoherent transport have to be considered: (i) carriers are generated by the dephasing time T_2 of the Bloch oscillations; (ii) the carriers are generated by the Gaussian profile of the laser pulse, i.e. $T_2 \rightarrow 0$. Furthermore, the holes are assumed to be localized in their wells. The results of the calculations, shown in Fig. 6, depict a ***linear*** screening of the applied electric field when the dephasing time of the Bloch oscillations is considered. A deviation from this linear dependence is obtained if the carriers are generated by the pump pulse. Additionally, the quantitative comparison of the field screening velocities obtained in theory and experiment yields a slight difference of only 10 %. Since we observed a linear field screening in the experiment, this result strongly confirms our model of a transition from the coherent to the incoherent, drift-like transport of the coherently excited electrons.

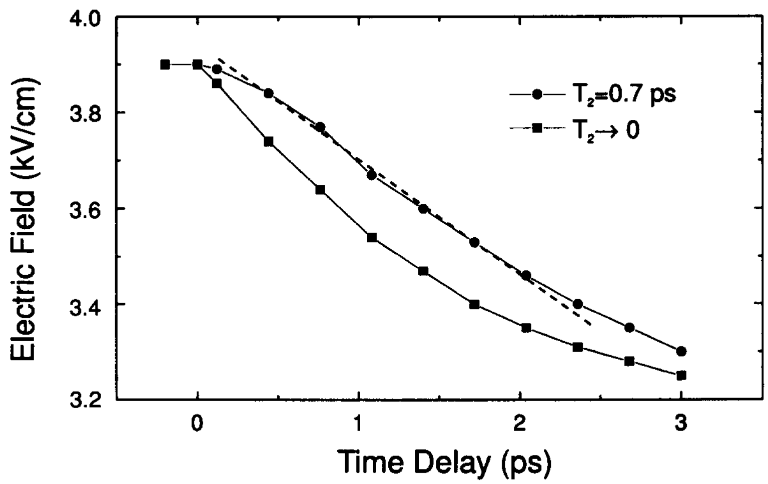

Figure 6: Electric field in the center of the superlattice calculated from the one-dimensional drift-diffusion model for an initial field strengths.

2.3.3 Excitonic thermalization dynamics in an InGaAsP/InGaAsP multiple quantum well

The main obstacle for the observation of Bloch oscillations at room temperature is the ultrafast thermalization of optically excited carriers. Therefore, the thermal dissociation of resonantly excited excitons in a shallow $In_{0.66}Ga_{0.34}As_{0.93}P_{0.07}/In_{0.77}Ga_{0.23}As_{0.47}P_{0.53}$ multiple quantum well structure was investigated. The sample was grown by the group of Prof. Abstreiter (Walter-Schottky Institute, TU München, Germany). The first excitonic transition of the MQW is located at 1.54 μm at room temperature.

For this investigation time-resolved transmission changes were detected at lattice temperatures from 10 K to room temperature and various excitation densities. The spectral profile of pump and probe pulse covered the excitonic transition at each temperature. The detected transmission changes are then dominated by the bleaching of the optical transition by the incident pump pulse due to phase space filling. Thus, the population of the excitons after optical excitation can be observed on the sub-picosecond time scale (see Fig. 7(a)). The exponential decay of the signals after the initial stage is attributed to the ionization of the excitons due to scattering processes. For a determination of the relevant scattering processes, the ionization times were extracted dependent on lattice temperature and excitation density. The scattering rates are then given by the inverse ionization times.

The exciton ionization time increases from 180 fs at room temperature to 450 fs at the lowest excitation densities. This temperature-dependence points towards the absorption of thermally populated

LO phonons being the dominant process for the exciton ionization. This is confirmed by the independence of the scattering time at a given lattice temperature under variation of the excitation density for temperatures above 150 K (not shown). More detailed, the scattering rates should increase linearly with the thermal population of the LO phonons that is given by Bose-Einstein statistics. Fig. 7(b) depicts the expected temperature dependence of the scattering rates. Thus, LO phonon scattering is concluded to be the dominant scattering mechanism at elevated temperatures. In contrast, at low lattice temperatures the scattering times decrease with increasing excitation densities. Here, the LO phonon population almost vanishes and the excitons are ionized by scattering at simultaneously excited free carriers in the electronic and hole sub-bands. The exciton-carrier scattering depends on the excitation density and, thus, yields the observed result.

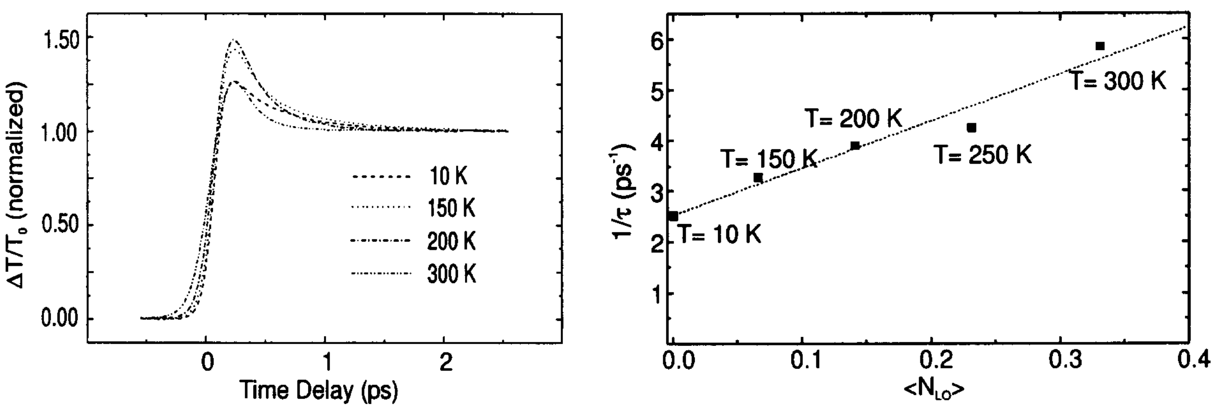

Figure 7: (a) Time-resolved resonant transmission changes detected in an InGaAsP/InGaAsP MQW at different lattice temperatures. (b) Scattering rates of the excitons dependent on the thermal LO phonon population. The dotted line is a linear fit to the experimental data.

3 Conclusions

Within the project period of one year several achievements in the field of ultrafast optoelectronics could be accomplished. Coherent carrier dynamics in externally biased superlattices, i.e. coherent Bloch oscillations, have been observed for the first time in InGaAs/InGaAs superlattices. This observation is an important extension of this field, since for the time being all activities on Bloch oscillations have been concentrated world-wide on MBE grown GaAs/AlGaAs superlattices. The dephasing times at low lattice temperatures are only a factor of 3 smaller than the largest dephasing times observed in the mature GaAs/AlGaAs system. Our observations provide first steps towards the realization of Bloch oscillations excited by compact 1.55 μm fiber lasers. The main potential for optimization is the decrease of impurity and interface scattering, which is expected to be accomplished in MBE grown samples. Several peculiarities have been observed in the density and field dependence of the Bloch oscillations' dynamics. A field dependence of the chirp of the oscillations could be identified as a transient screening of the applied electric field by scattered carriers. A shift in the onset of Bloch oscillations versus the optical excitation densities could be identified as a static accumulation of the optically excited carriers in the specific sample design. The lower limit of the frequencies was 1 THz, while the upper limit of 2 THz was given by the spectral width of our laser pulses. The lower limit will be further decreased by higher sample quality, while the upper limit will be increased by the use of shorter laser pulses and stronger coupled superlattices. In addition, the use of superlattices with higher numbers of periods (> 10) will strongly enhance the internal Bloch oscillations' amplitude as well as the emitted THz power.

4 Publications and presentations

The following results obtained within the project were published:

1. M. Först, G.C. Cho, T. Dekorsy, and H. Kurz, "Chirped Bloch oscillations in strain-balanced InGaAs/InGaAs superlattices", accepted for publication in a special issue of *Superlattices & Microstructures* on ultrafast phenomena, quantum-optical effects, etc. in July 1999.

2. M. Först, G.C. Cho, T. Dekorsy, H. Kurz, A. Nutsch, and G. Abstreiter, "Ultrafast thermalization dynamics in InGaAsP/InGaAsP quantum wells", Technical Digest *European Quantum Electronics Conference* (Institute of Electronical and Electronics Engineers, Piscataway, 1998), p. 146.

Additionally, the results have been or will be presented at the following conferences:

1. M. Först, G.C. Cho, T. Dekorsy, and H. Kurz, "Time-resolved coherent and incoherent carrier transport in InGaAs/InGaAs superlattices", oral presentation at the *Spring Meeting of the German Physical Society*, Regensburg, Germany, 23-27 March 1998.

2. M. Först, G.C. Cho, T. Dekorsy, and H. Kurz, "Bloch oscillations in an InGaAs/InGaAs superlattice", **invited talk** at the *17th General Conference of the Condensed Matter Division of the European Physical Society*, Grenoble, France, 25-29 August 1998.

3. M. Först, G.C. Cho, T. Dekorsy, and H. Kurz, "Detection of Bloch oscillations in InGaAs/InGaAs superlattices", poster presentation at the *Scottish Universities Summer School in Physics 52: Advances in Lasers and Applications*, St. Andrews, Scotland, 5-13 September 1998.

4. M. Först, G.C. Cho, T. Dekorsy, H. Kurz, A. Nutsch, and G. Abstreiter, "Ultrafast thermalization dynamics in InGaAsP/InGaAsP quantum wells", poster presentation at the *European Quantum Electronics Conference*, Glasgow, Scotland, 14-18 September 1998.

5. M. Först, G.C. Cho, T. Dekorsy, and H. Kurz, "Chirped Bloch oscillations in InGaAs(P)/-InGaAs(P) superlattices", submitted to the *Quantum Electronics and Laser Science Conference*, Baltimore, Maryland, 23-28 May 1999.

The support of the U.S. Army, which enabled us to perform these studies, has been acknowledged in all publications and presentations.

5 Scientific personnel and collaborations

The following people in the Institute contributed to the achievements within the first project year:

- Prof. Dr. Heinrich Kurz, head of the Institute, principal investigator.
- Dr. Thomas Dekorsy, research coordinator.
- Dr. Peter Haring-Bolivar, research associate.
- Dipl.-Phys. Michael Först, fs-spectroscopy.
- Dipl.-Phys. Gordon Bartels, theory of coherent effects in semiconductor heterostructures.
- Mrs. Denise Debey, technical assistance (sample preparation).
- Mr. Konrad Elbern, technical assistance (laser maintenance).

In addition, collaborations with the following institutes were arranged during the project:

- Prof. K. Heime, Institute of Semiconductor Electronics I, RWTH Aachen: fabrication of InGaAs/InGaAs superlattices.

- Prof. G. Abstreiter, Walter-Schottky Institute, TU München: fabrication of InGaAsP/InGaAsP multiple quantum wells.
- Prof. A. Stahl, theory group at the RWTH Aachen: theory of optical nonlinearities and coherent effects in semiconductors and semiconductor heterostructures.

With Dr. R.P. Leavitt, Adelphi Laboratories, we discussed sample structures to be investigated and the possibility to visit Adelphi Labs. A meeting of Dr. Dekorsy with Dr. Leavitt is envisaged around the time of the CLEO/QELS '99 meeting to be held in Baltimore, MD, in May 1999.

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